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p. 18

FINAL REPORT FOR NASA-LANGLEY CONTRACT #NAG-1-1157

A. "VELOCITY PROFILES IN A HOT JET BY SIMPLIFIED RELIEF"

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INTRODUCTION

The principal goal of this research effort has been to provide support for the installation of simplified RELIEF (1) flow tagging instrumentation at NASA-Langley Research Center. RELIEF is a double resonance velocimetry technique in which oxygen molecules are vibrationally excited via stimulated Raman scattering at a specific location within a flow field. After suitable time delay, typically 1-10 microseconds, the displacement of the tagged molecules is determined by laser-induced fluorescence imaging.

The current work has centered around characterization and optimization of a high-pressure O_2 stimulated Raman cell, which greatly simplifies the tagging step. During the work period, conversion efficiency and spectral profile measurements have been performed under a variety of conditions, and a 2 m long cell has been installed at NASA-Langley. Additionally, limited work has been performed on improvements to a high-intensity, ultraviolet flashlamp, which was used, for the first time, to obtain images of vibrationally excited oxygen in a low-speed O_2 jet. The ultimate goal of this part of the effort is to find a substitute for the argon-fluoride laser which is currently used for the laser-induced fluorescence interrogation step.

REVIEW OF WORK PERFORMED

A. Characterization of Stimulated Raman Cell

1. Conversion Efficiency

The vibrational tagging step requires two high power laser beams with frequency difference equal to the vibrational frequency of oxygen. In the original RELIEF experiments, the second laser beam was derived from the first using a dye laser. This required that the primary laser beam be split into two parts, one of which pumped the dye laser and, subsequently, that the two beams be recombined. The two laser beams had to be overlapped in time, space, and frequency, and the primary beam had to be powerful enough to pump the dye laser, which is not a particularly efficient process. Recently (2), we have developed a high pressure O_2 stimulated Raman cell which directly converts a portion of the primary beam to the desired second wavelength. The two beams exit the cell automatically matched in frequency and time, and with excellent spatial overlap.

In the last year, we have worked to optimize the Raman cell conditions by studying a variety of configurations. The results of these studies are summarized in Table I. As can be seen, three different cells have been examined. The first is a rather conventional 2 m long cell, which has been studied with a variety of focusing lenses in both single and double-pass modes. The second is a 6 m long cell, and the third is a 1 m long, cylindrical optics, multi-pass cell. We will now discuss these cells in more detail.

a. 2-Meter Cell

The 2 m cell has been studied in most detail because it is the simplest to both construct and to use in common laboratory environments. It has been determined that an approximately 1:1 mixture of O_2:He at 1000 psi total pressure is an optimum gas mixture for Q-switched YAG lasers with 250-300 mJ/pulse energy operating at 5-10 Hz repetition rate. The helium buffer serves to diffuse heat which is built-up along the beam waist due to the vibrational excitation which occurs as part of the conversion process. The total pressure must be fairly high because the Raman gain of oxygen is relatively low (less than 1/100th of H_2, for example, at STP).

Figure 1 shows 1st Stokes conversion efficiency (•) and fractional loss (o) as a function of input laser energy for 1.0, 1.5, and 2.0 m focal length focusing lenses, using the 2 m cell with a 450:550 psi O_2:He mixture. All data is taken using the second harmonic of a Nd:YAG laser at 0.532 microns, with ~10 nsec pulse duration and a repetition rate of 10 Hz. As discussed in Reference 2, the laser is operated in its broad-band mode which results in a linewidth of ~1 cm^{-1}. This, combined with a relatively long confocal beam parameter, serves to suppress stimulated Brillouin backscatter (SBS) which competes with the Raman conversion. As can be seen, use of the 1 m focal length lenses results in significant SBS energy loss (~60%) for all but the lowest input pulse energies. The corresponding conversion efficiency ranges from <1% at 65 mj/pulse to ~5% at 350 mJ/pulse. Increasing the focal length of the focusing lens to 1.5 m results in an increase in the conversion efficiency to ~8-9%, and a drop in the energy loss to ~20%. This configuration, with ~250-300 mJ of input energy is now

b. Other Cells

Limited experiments have been performed with a 6 m cell which was constructed by bolting three 2 m segments together, and a cylindrical multi-pass cell, based on an optical configuration used by Long, et al. (3) for increasing the sensitivity of Rayleigh scattering measurements. The 6 m cell, despite being certified to only 600 psi total pressure, gave a single-pass conversion using a 4 m focal length input lens in the 11-12% range. The SBS loss was negligible. The cylindrical cell gave the highest conversion efficiency (~30%) of all the cells used, but the repetition rate was limited to 1 Hz. The windows of this cell are 2" (~1-1/2" unsupported), so that the total working pressure is limited to 500 psi. Due to the multi-pass arrangement and the cylindrical focusing, thermal beam degradation is more significant in this cell, resulting in the low repetition rate. (It is anticipated that increasing the helium buffer partial pressure would result in some improvement.)

2. <u>Pressure-Shifting Measurements</u>

At the high pressures required for operation of the O_2 Raman cell, it is important to verify that the 1st Stokes frequency overlaps with that corresponding to O_2 at near 1 atm conditions. In order to verify this, we have performed simple scanning coherent anti-Stokes Raman spectroscopy (CARS) Q-branch measurements in the high-pressure cell and ordinary room air, simultaneously. As discussed in Reference 2, at high pressure, the individual rotational lines within the vibrational Q-branch merge into one feature. The results of these measurements are summarized in Figs. 3a and

3b. From Fig. 3a, which corresponds to pure O_2 at 450 psi, the high-pressure Q-branch overlaps almost perfectly with the J=7 transition at room conditions. In the 450:550 psi O_2:He mixture of Fig. 3b, the high-pressure Q-branch has shifted slightly (~0.3 cm^{-1}) and now peaks approximately midway between the J=7 and J=9 transitions at room conditions. Since the Nd:YAG pump beam has a spectral width of ~1 cm^{-1}, these results indicate that the 1st Stokes output from the cell should efficiently pump oxygen molecules in the J=7 and J=9 rotational levels.

B. Ultra-Violet Flashlamp Development

We have performed some limited additional work on the development of a high brightness, ultraviolet flashlamp for use as a flow interrogation source. A schematic of an earlier lamp design is shown in Fig. 4. The lamp, based upon a design of Holzrichter and Emmett (4), is a windowless, coaxial discharge lamp which uses flowing helium gas. In a prior reporting period (5), we measured the spectral and spatial light output of the lamp and obtained an estimated effective blackbody temperature of ~25,000 K.

During this work period, it was determined that a significant amount of energy was dissipated across the spark gap, and that the spark gap was also a significant source of inductance. Removal of the spark gap resulted in a decrease in the pulse duration, and a large increase in the UV pulse energy. In the last report, a pulse energy of 0.06 mJ (in an ~10 nm spectral band centered at 185 nm), and a pulse duration of ~12 microseconds was obtained using a 2 μF capacitor and 8 KV charging voltage with helium flow gas. Upon removal of the spark gap, using a 5 F capacitor and a 5-6 KV charging voltage, the pulse duration was reduced to ~5 microseconds, and the UV pulse energy in the same band was increased to greater than 1 mJ/pulse. These pulse energies are measured with a pyroelectric joulemeter, purchased with previous funding for this research. The energies represent net numbers, obtained by subtraction of measured energies without nitrogen pumping of the optical system, from measured energies including purging. The spectral filtering of the very broad band lamp output is performed with a pair of ArF lasers 193 nm high reflectors tilted off-axis to shift the peak of the reflectivity. This is illustrated in Fig. 5, which shows the optical configuration and the measurement location. Figure 6 shows the resulting spectral band.

Spectral scans were performed using the optical set-up of Fig. 5, but with a purgable spectrometer in place of the joulemeter. Figure 7 shows two traces, the upper being with a nitrogen purge, the lower without. The spectrometer does not have a UV grating, and so the sensitivity falls off rapidly with deceasing wavelength. It is clear, however, that the flashlamp is producing significant light flux in the 185 nm region.

This increased vacuum UV intensity has enabled us to obtain, for the first time, RELIEF images of vibrationally excited oxygen using the Raman cell to tag, and the flashlamp to interrogate. A typical pair of images is illustrated in Fig. 8. The flashlamp optical set-up is similar to that of Fig. 5, except that the 50 mm focusing lens was positioned as close as possible to the inner wall of the purgable enclosure. (The air path between the lens and the focus was not purged.) The focal volume of the flashlamp output was approximately cylindrical, 3mm in diameter by 1-2 cm long. The tagging beams from the Raman cell were focused with a 300 mm lens, and intersected the flashlamp interrogation volume at a slight (~5^{o}) angle. The resulting images were captured at 90^{o} with respect to the tagging beams using a UV-intensified CID camera and a Corning 7910 glass filter. It was found that this filter, while decreasing the signal, increased the contrast between the tagged line and the background.

The images in Fig. 8 appear fuzzy due to the relatively long exposure time from the flashlamp. There is also significant background from O_2 Schumann-Runge fluorescence, which has a large cross section in the 180-185 nm region. It is anticipated that further work will allow us to significantly improve upon the quality of these images.

SUMMARY AND FUTURE WORK

The Raman cell has been developed and characterized to the point where it is now the method-of-choice for O_2 flow tagging. It is routinely used in two of our laboratories, and a cell has been constructed and operated at NASA-Langley Research Center. The output of the UV flashlamp has been increased by more than a factor of ten, and the first RELIEF images of vibrationally tagged oxygen have been obtained.

Future work, contingent upon continued support, will focus on collaboration between Princeton and NASA-Langley in performing flow tagging measurements in NASA LARC facilities. Further development of the UV flashlamp, with the goal of improved sensitivity, contrast, and timing, is also anticipated.

REFERENCES

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3. M.B. Long, P.S. Levin, and D.C. Fourguette, Opt. Lett 10, p. 267-269 (1985).

4. J.F. Holzrichter and J.L. Emmett, Appl. Opt. 8, p. 1459 (1969).

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TABLE I

SUMMARY OF CELLS INVESTIGATED

	Cell	f_L	Pulse Duration	Gas Mix (O_2:He)	%1st Stokes	Emax
1.	2 m	2 m	10 nsec	450:0	3-4%	50 mJ
2.	2 m	1-2 m	10	450:550	4-9%	>250 mJ
3.	2 m	1 m	5	450:550	8%	>250 mJ
4.	2 m (2 passes)			400:600	~17%	>220 mJ
5.	6 m	4 m	10	200:400	11-12%	>250 mJ
6.	1 m *(Cylindrical Multipass - 9 passes - Limited to 1Hz)*					
			10	400:100	~30%	>250 mJ

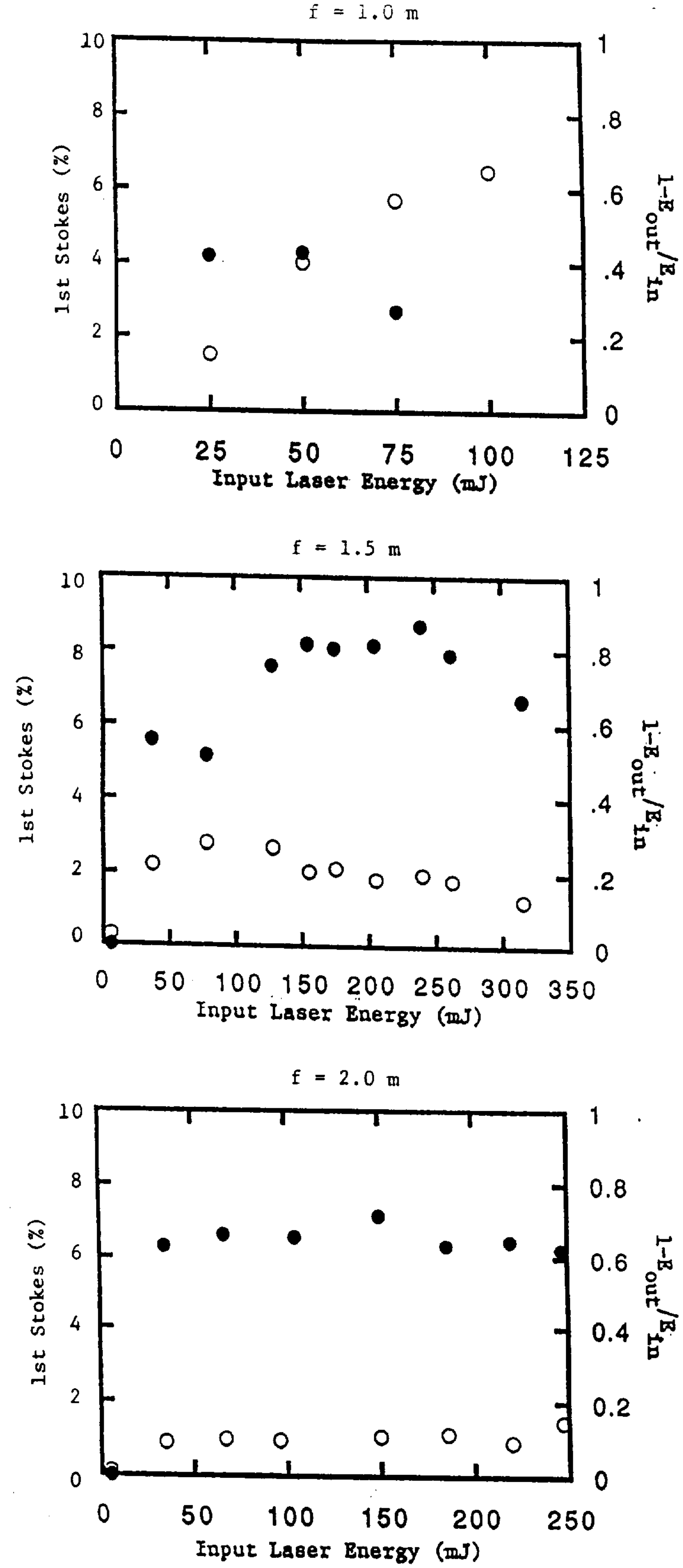


Figure 1. 1st Stokes Conversion Efficiency (o) and Fractional Loss (o) as a Function of Laser Pulse Energy for 1.0, 1.5, and 2.0 m Focusing Lens.

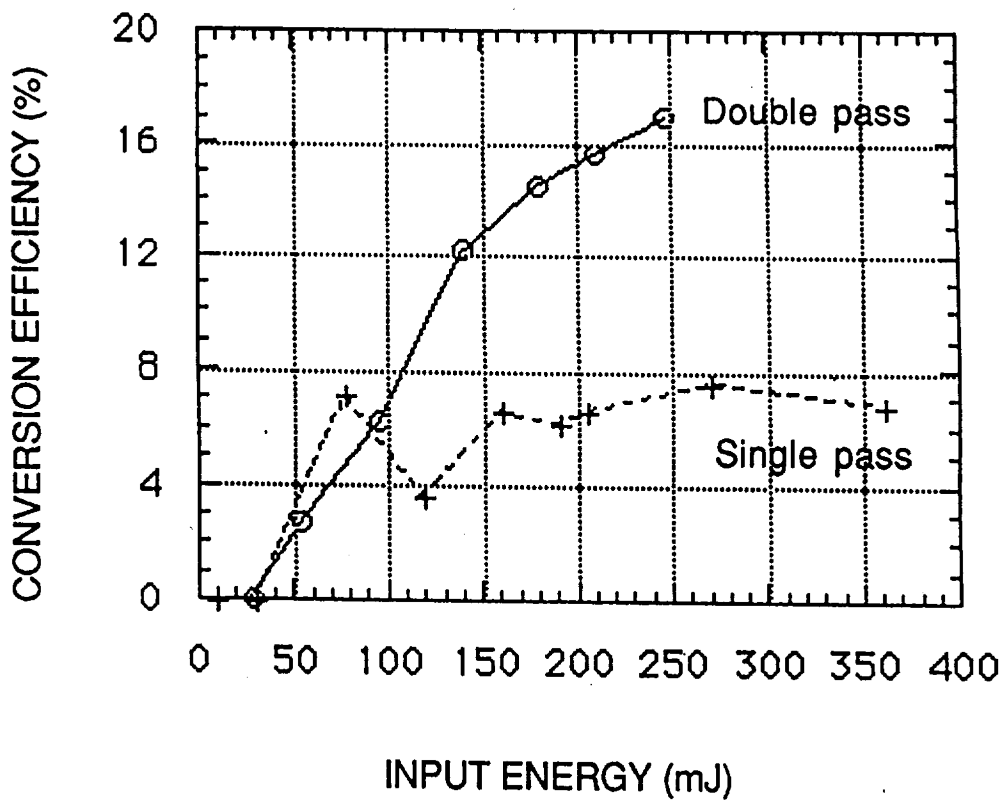


Figure 2. Single Pass (+) and Double Pass (o) 1st Stokes Conversion Efficiency for 5 nsec Pulse Duration Laser. The Cell Length is 2.0 m and Focusing Lens Focal Length is 1 m.

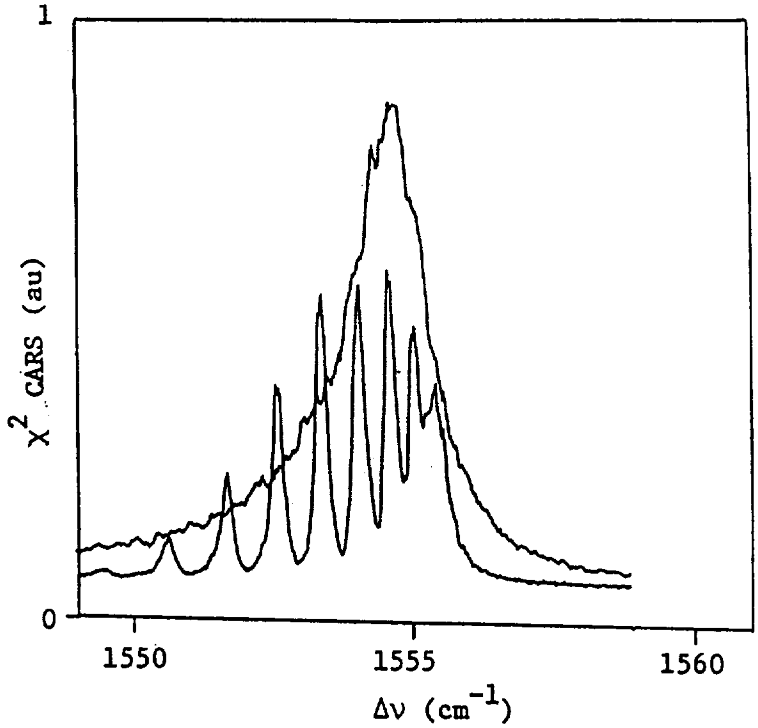


Figure 3a. Experimental CARS Spectra for Pure O_2 at 450 psi (Upper Trace), Along with Room Air Reference (Lower Trace).

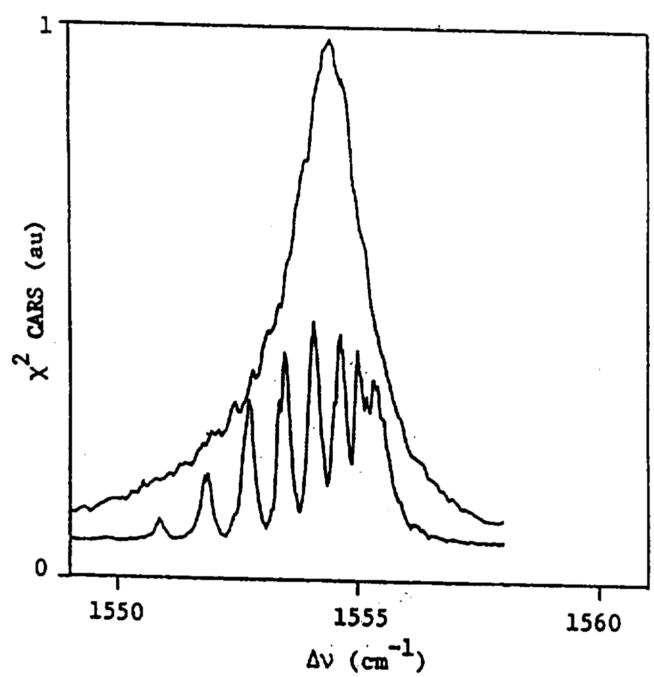
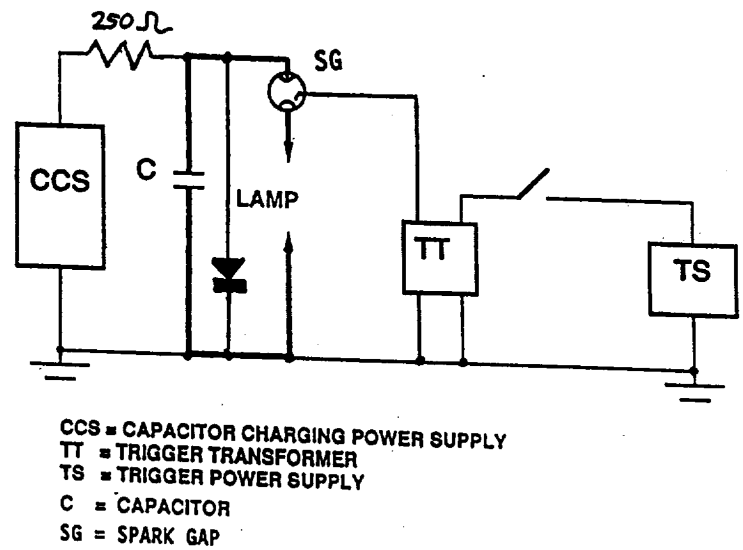


Figure 3b. Experimental CARS Spectra for Mixture of 450 psi O_2 and 550 psi He (Upper Trace), Along with Room Air Reference (Lower Trace).



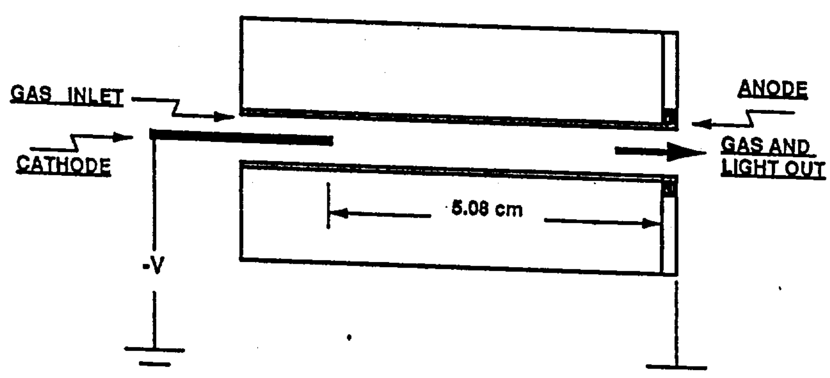


Figure 4. Schematic Diagram of Original Version of Coaxial UV Flashlamp. The Spark Gap has been Removed from the Current Version.

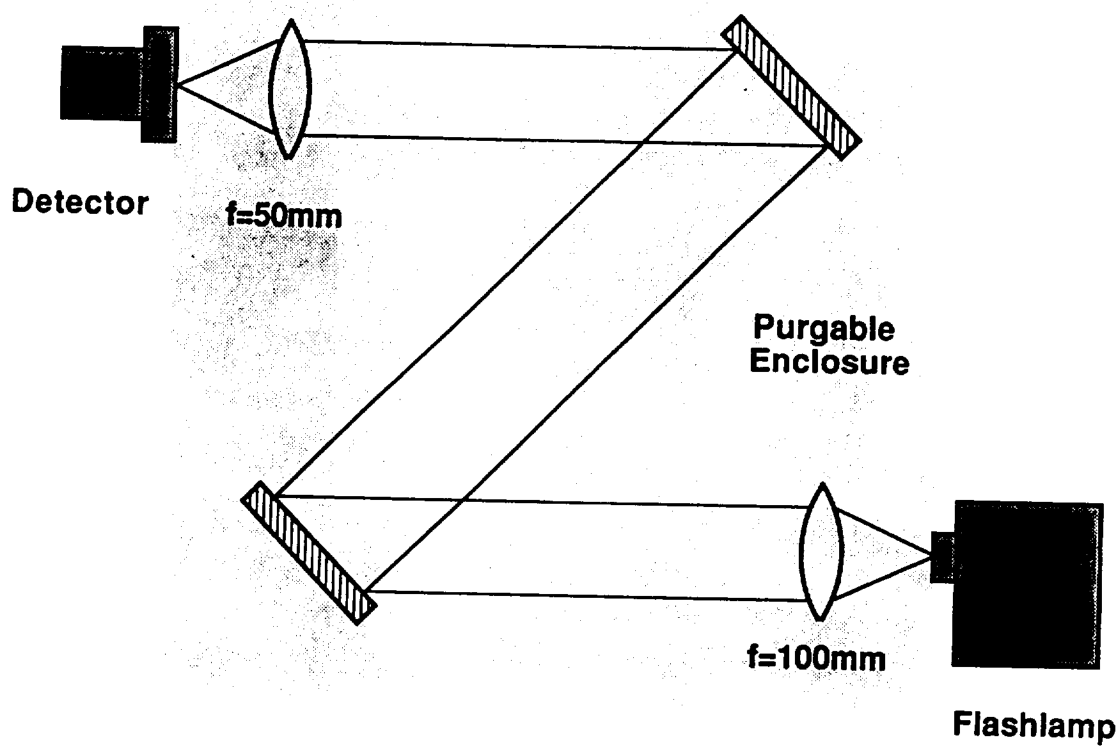


Figure 5. Schematic Diagram of Flashlamp Optical Filtering and UV Energy Measurement.

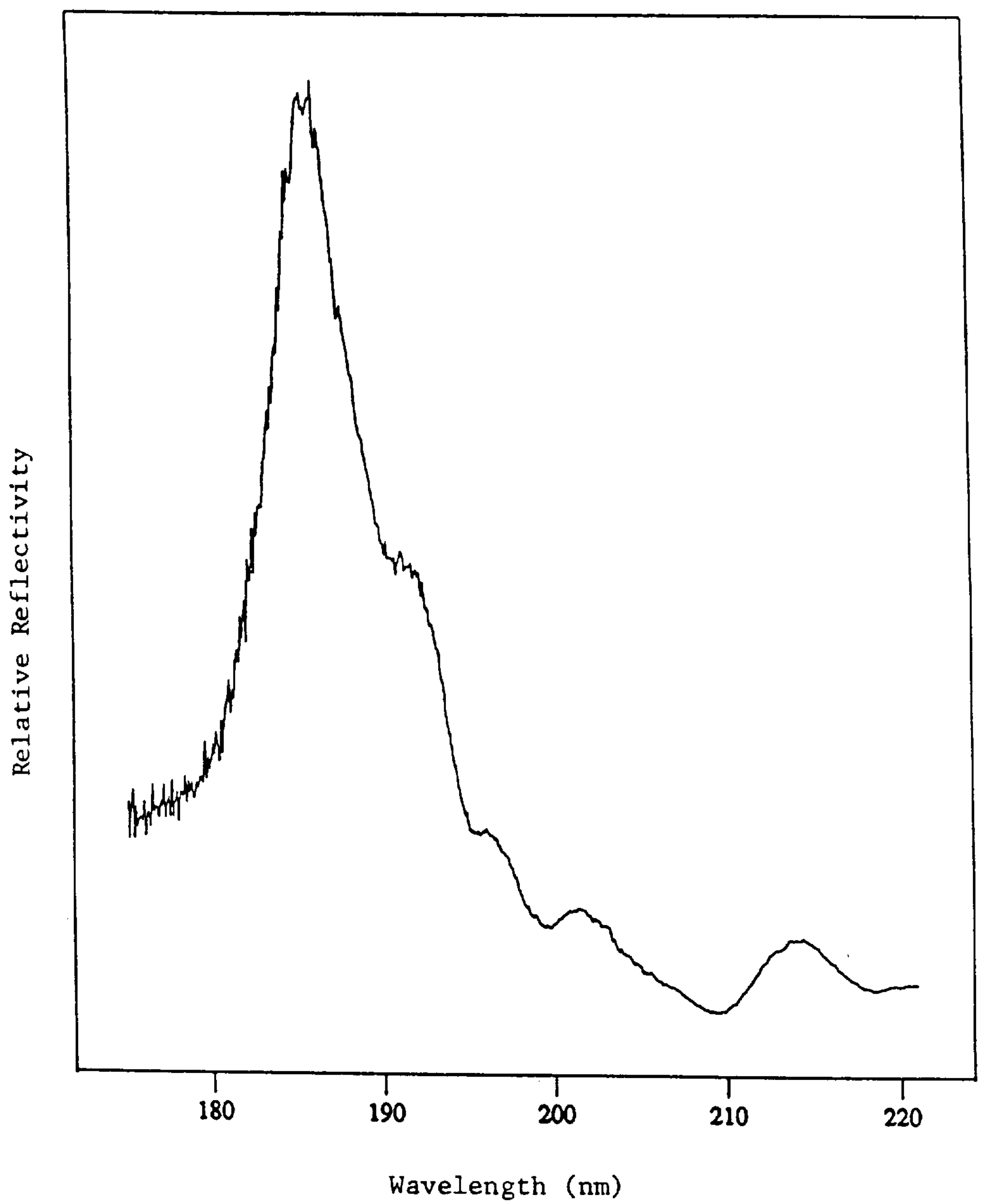


Figure 6. Relative Reflectivity of Mirror Pair as a Function of Wavelength.

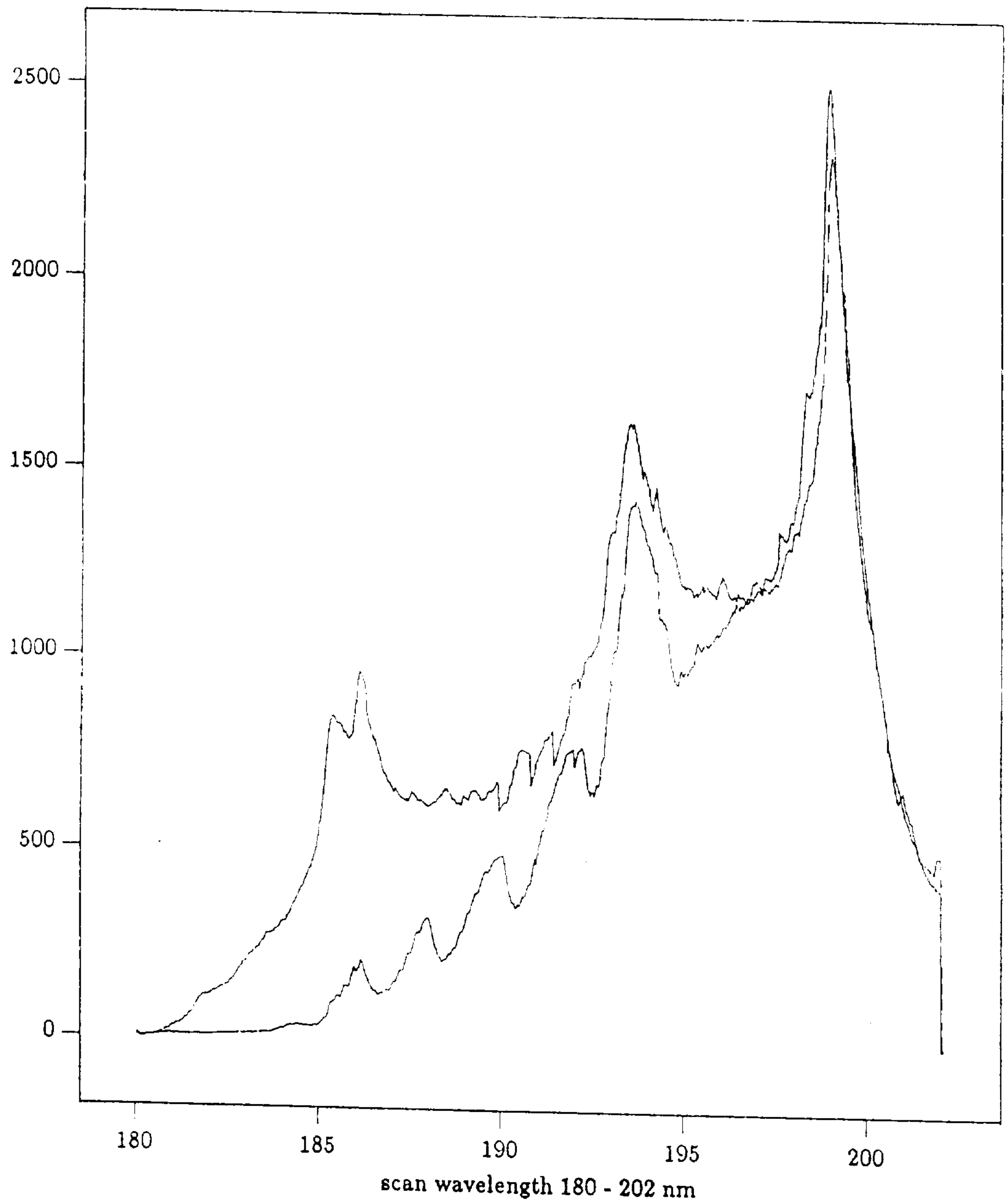


Figure 7. Experimental Lamp Output as Function of Wavelength With (Upper Trace) and Without (Lower Trace) N_2 Purge of Optical Path.

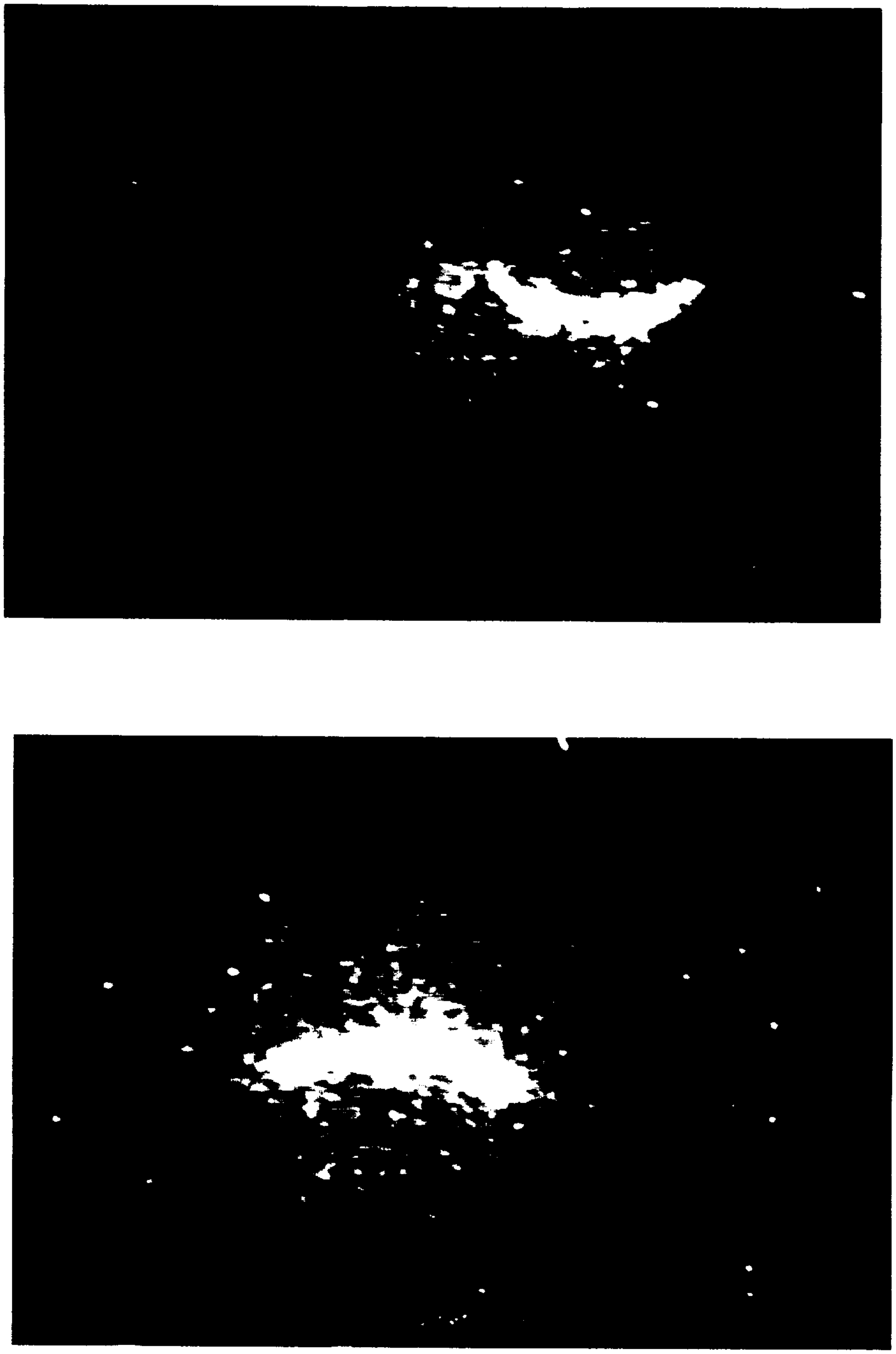


Figure 8. Selected Images of Displaced Lines Using Raman Cell for Tagging and UV Flashlamp for Interrogation.